Appendix C

Uncertainty in Emissions Estimates

Overview

The Energy Information Administration (EIA) has prepared so-called “Tier I" estimates of the reliability of the different methods used to estimate emissions in the main report. Also, EIA has begun to conduct a “Tier II” analysis of these same data. For details on the preliminary results of the “Tier II” analysis for energy-related carbon dioxide emissions see the text box in Chapter 2 of the main report.

For either “Tier I” or “Tier II” analysis the sources of uncertainty fall into the categories outlined below:

- Uncertainty associated with underlying activity data and uncertainty associated with emissions factors
- Random errors and bias errors
- Potential for upward and downward bias errors
- Reliability of emissions estimates by source.

The distribution of uncertainty estimates is summarized in Table C1, which excludes estimates for emissions and sequestration from land use changes and forestry. Summarizing all the uncertainties, it is possible that U.S. national greenhouse gas emissions, taken as a group, may differ by as much as 12 percent from the estimates in this report. Much of the uncertainty in national emissions comes from nitrous oxide emissions, for which estimates are accurate only to within 100 percent and which accounts for about half the uncertainty in the national estimate. Excluding this source, the uncertainty of the total estimate is less than 10 percent.

The bulk of the potential uncertainty in the overall national estimate takes the form of bias errors, which are likely to persist from one year to the next and, thus, have relatively little influence on trends, rather than random errors, which would increase the difficulty of determining whether or not a trend exists. This is because estimates of energy-related carbon dioxide are probably accurate to well within 10 percent of estimated emissions, and energy-related carbon dioxide accounts for 81 percent of national emissions of greenhouse gases. There are much larger uncertainties for methane and, particularly, for nitrous oxide emissions, but the present evidence suggests that emissions from these sources accounts for only a small portion of total emissions.

Table C1. Estimate of the Reliability of 1999 U.S. Emissions Estimates (Tier 1 Method)

Greenhouse Gas Source	Share of Total Emissions	Activity Data Bias		Activity Data Random	Emissions Factor Bias		Emissions Factor Random	Weighted by Total Emissions	
		Min	Max		Min	Max		min	max
	<----------Percent of Source---------->							Percent of Total	
Carbon Dioxide									
Petroleum	35.2%	2.1%	2.4%	0.5%	1.7%	1.7%	0.5%	1.0%	1.1%
Coal	29.9%	0.6%	4.3%	0.6%	1.0%	1.0%	0.5%	0.4%	1.4%
Natural Gas	17.2%	0.5%	2.8%	0.5%	0.0%	0.0%	0.4%	0.1%	0.5%
Other	0.6%	-9.3%	7.8%	11.1%	23.3%	23.3%	4.4%	0.2%	0.2%
Missing Sources	0.0%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%
Total	82.9%	1.1%	3.7%	0.6%	1.2%	1.2%	0.5%	1.7%	3.5%
Methane									
Energy-Related	3.2%	13.2%	14.0%	4.9%	20.8%	25.0%	4.5%	0.8%	0.9%
Agricultural	2.8%	3.1%	5.0%	3.0%	36.4%	36.4%	10.6%	1.1%	1.1%
Industrial & Waste	3.2%	9.7%	29.4%	5.0%	50.5%	13.8%	10.1%	1.6%	1.1%
Missing Sources	0.0%	0.0%	4.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total	9.2%	8.9%	20.6%	4.3%	35.9%	24.6%	8.3%	3.5%	3.1%
Nitrous Oxide									
Energy-Related	1.3%	0.5%	2.8%	0.5%	55.0%	200.0%	10.0%	0.7%	2.5%
Agricultural	4.1%	4.0%	5.0%	4.5%	90.0%	100.0%	10.0%	3.7%	4.1%
Industrial & Waste	0.4%	2.8%	5.0%	3.5%	55.0%	200.0%	10.0%	0.1%	0.5%
Missing Sources	0.0%	0.0%	15.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.5%
Total	5.7%	3.1%	19.5%	3.5%	80.0%	128.5%	10.0%	6.5%	7.5%
HFCs, PFCs, SF6									
HFCs, PFCs, SF6	2.2%	4.5%	2.4%	0.9%	13.8%	15.5%	2.5%	0.5%	0.6%
Missing Sources	0%	0.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
Total	2.2%	4.5%	12.4%	0.9%	13.8%	15.5%	2.5%	0.5%	0.6%
Total-All Sources	**100.0%**	**2.0%**	**6.4%**	**1.1%**	**9.2%**	**11.0%**	**1.8%**	**13.2%**	**12.9%**

Notes: The "low" and "high" bias errors provide a subjective estimate of the largest bias error lower or higher than the current point estimate that would be consistent with current understanding of the nature of the activity or emissions mechanism. Each value is calculated as the weighted average of the uncertainties associated with a group of sources in each category. It is calculated as a percentage of the point estimate of emissions from that source. "Random error" is a subjective estimate of the largest random error that is consistent with current understanding of the nature of the activity or emissions estimate. "Weighted uncertainty" is calculated as the square root of the sum of the squared activity factor and emissions factor errors and then multiplied by the point estimate of the share of total emissions for the source. It is calculated as a percentage of the point estimate of total 1997 U.S. emissions.
Source: Estimates presented in this Appendix.

The uncertainties in the estimates presented in this report come from the following sources:

- **Evolving Definitions.** In general, this report attempts to measure “anthropogenic” (human-caused) emissions and sequestration of greenhouse gases in the United States, excluding carbon emissions of biological origin. Although in most cases it is obvious whether emissions from a particular source fall within this definition, there are a number of ambiguous cases, and the range of accepted definitions has shifted over time. Since the first edition of this report, sulfur hexafluoride has been added to the generally accepted definition of “greenhouse gases.” Emissions from bunker fuel are now excluded from the definition of “U.S. emissions.” Definitional changes tend to raise or lower emissions estimates systematically.

- **Emissions Sources Excluded From the Report.** An estimate that excludes some sources will be biased downward by the amount of the excluded source. Of course, if the existence or magnitude of the excluded emissions were known, they would be included. But it is probable that there are still sources that have not yet been identified and escape inclusion in both the estimates and the list of sources excluded.

- **Incorrect Models of Emissions Processes.** An estimate based on a belief that emissions are caused by (or can be estimated from) a particular activity or process can produce large, systematically biased errors if the emissions are actually caused by some other process. The incorrect method can produce estimates that are considerably higher or lower than actual emissions and have different time-series properties.

- **Errors in Emissions Factors.** Errors in emissions factors can have diverse causes, the most common of which are definitional errors, sampling errors, and measurement errors. These errors can be either random or systematic.

- **Errors in Activity Data.** Activity data are also subject to definitional errors, frame errors, sampling errors, and measurement errors, which can be either random or systematic.

- **Computational Errors.** Computational errors can exist in the estimation of emissions factors by EIA, in the calculation of emissions by EIA, or in the computation of the underlying activity data by the source organization. Although any single computational error will usually produce a systematic error, computational errors as a group tend to produce very small (about 0.1 percent) random errors in the estimate.[1]

The different sources of error, as noted above, can produce random or systematic ("bias") errors. Random errors have the appearance of "noise" in the estimate, causing random year-to-year changes in the estimate as compared with (unobservable) actual emissions. Random errors might be caused by data collection and computation errors, the inherent imprecision of metering and measurement, and timing problems. Thus, it should be difficult to distinguish the "signal" of growing or declining emissions until the magnitude of the trend exceeds the "noise" from the random fluctuations. Since, in the case of U.S. energy data, rather small trends in the underlying data can be detected, it is likely that the aggregate magnitude of random errors in U.S. energy data is small, and, in particular, smaller than bias errors.

Bias errors will produce an error of approximately the same magnitude every year. If bias errors are small, they are not likely to affect the estimates of trends. Excluded sources and changes in definition produce bias errors. "Double counting" in activity data surveys will produce upwardly biased estimates of the activity; frame errors or other forms of undercounting will produce estimates that are biased downward. Because EIA, like other statistical agencies, produces data by approximately the same methods every year, double counting and undercounting errors are likely to persist over time.

There is no reason to believe that the distribution of bias errors is symmetrical around the point estimate of the value. In fact, *a priori* or independently gathered information may indicate that the potential size and probability of the existence of bias errors may be skewed: for example, in EIA data it is likely that essentially all the transactions reported to EIA actually occurred; however, it is possible that some transactions were never reported. Thus, EIA energy data are more likely to underestimate than to overestimate actual energy consumption. Further, because there are multiple surveys of energy production and consumption, undertaken for multiple purposes, the results of the surveys can help put bounds on the extent of possible bias errors.

Bias errors can be hard to detect, and it is hard to prove either the presence or absence of bias errors. The best ways of detecting them are to use multiple methods of estimating the source series and compare the results, or to determine the range of possible values from *a priori* information. Comparison methods usually can establish "ceilings" and "floors" for bias errors: that is, it is possible to demonstrate that if the bias error exceeds a certain percent, then a separate,

[1]Every year, as this report is prepared for publication, a number of computational errors that have crept into the report are detected and fixed. Sometimes, the detected errors have been present for more than one year. The errors that have been detected are typically very small (about 0.01 to 0.1 percent of emissions) and subtle, and they tend to both raise and lower estimated emissions. EIA is not aware of any remaining computational errors, but it is assumed that any undetected errors generally are similar to, or smaller than, the errors that have been detected.

independently collected series must also have a bias error of the same sign. An investigation of how the data are collected may also uncover information about the magnitude or scale of potential bias errors.

The reliability of emissions data varies by category and by source. In general, estimates of carbon dioxide emissions are more reliable than estimates for other gases. It is likely that the estimate of carbon dioxide emissions is accurate to within 5 percent, suggesting an emissions range from 1.3 billion to 1.5 billion metric tons.

Estimates of methane emissions are much more uncertain. The level of precision is probably on the order of 30 to 40 percent. Estimates of methane emissions are also likely to understate actual emissions, as a result of the exclusion of sources that are unknown or difficult to quantify such as abandoned coal mines or industrial wastewater.

Nitrous oxide emissions estimates are much more unreliable than carbon dioxide or methane emissions estimates, in part because nitrous oxide emissions have been studied far less than emissions from other sources and in part because the largest apparent sources of nitrous oxide emissions are area sources that result from biological activity, which makes for emissions that are highly variable and hard to measure or characterize. The uncertainty for the principal source of nitrous oxide emissions appears to be on the order of 100 percent, and there may be significant missing sources.

Carbon Dioxide

Sources of Uncertainty

Most carbon dioxide emissions estimated in this report result from the combustion of fossil fuels. The uncertainties in estimates of emissions from fossil fuel combustion can be divided into four types:

- **Uncertainties in the Volumes of Fuel Consumed.** In general, volumetric fuel data are believed to be fairly reliable, plus or minus about 3 to 5 percent; estimates of total consumption by fuel are more reliable than estimates by sector or by particular product.

- **Uncertainties in the Characteristics of Fuel Consumed.** Fuel data are collected on a volume or weight basis, but the density and energy content of fuels must often be estimated. The energy content of natural gas is reliable to 0.5 percent, but the reliability of energy content estimates for coal and petroleum products is lower.

- **Uncertainties in the Emissions Coefficients.** Emissions coefficients can be computed with a high degree of precision for a particular fuel sample on the basis of a laboratory analysis. If the characteristics of a fuel are difficult to measure accurately, however, the emissions coefficient for the sample fuel may not match the actual characteristics of the fuel consumed. The pipeline-quality natural gas coefficient is probably accurate to within 1 percent, but the reliability of the coal and petroleum product coefficients is lower, because they are more heterogeneous fuels.

- **Uncertainties of Coverage.** These uncertainties may arise from excluded or unknown sources of emissions.

Fuel Consumption

In general, energy statistics produced by EIA are most accurate for energy industries that are highly concentrated and/or heavily regulated and least accurate for activities that are decentralized, with large numbers of producers or consumers, and for fuels that have many heterogeneous states. It is impossible to be certain about the absolute magnitude and distribution of errors in the energy data, but it is likely that most are bias errors rather than random sampling errors. EIA collects the same data from nearly the same respondents every year (although survey frames are systematically updated), using nearly the same methods. Product flows that escape the coverage of the statistical system are likely to stay outside the statistical system from one year to the next. Similarly, if respondents make undetected definitional or computational errors (for example, misclassifying a petroleum product), they are likely to repeat their mistakes for prolonged periods.

There is indirect evidence in favor of the relative unimportance of random error in energy statistics, in the form of the relative lack of variability of the statistics compared with other economic time series. That most EIA surveys are

censuses, with what is intended to be 100-percent coverage of eligible respondents, rather than small sample surveys, reduces the scope for random errors.

If, as is suspected, random error is relatively unimportant, then most of the error is bias error, made in essentially the same way every year. Therefore, while the level of U.S. emissions of carbon dioxide could be systematically lower or higher than reported here, the reported trends over time are more likely to be reliable than the uncertainties in the energy data would suggest. Since energy production and consumption are covered by multiple surveys, it is possible to use this information to gain insight into the possible uncertainties in the energy data.

Coal. Coal production and consumption data are based on weight—short tons of coal. Coal consumption by regulated electric utilities, including both tonnage and energy content, is universally reported to EIA and the Federal Energy Regulatory Commission (FERC). In 1998, utility coal consumption accounted for about 87 percent of U.S. coal consumption.[2] There are likely to be only minor errors (around 1 percent) in reported utility coal consumption. Industrial, residential, and commercial coal consumption estimates are subject to potentially larger errors, especially in the counting of residential and commercial sector consumption; however, residential and commercial coal consumption is very small, and even large errors would have a negligible impact on emissions estimates. The statistical discrepancy for coal production (the difference between reported consumption and reported production less exports, plus imports, plus stock changes) averaged less than 10 million metric tons, or less than 1 percent of consumption, in the period 1993-1998.[3]

Natural Gas. Most natural gas is sold or transported by State-regulated local distribution companies. Excluding imports, the statistical discrepancy for natural gas has an average value of between 2 and 3 percent of consumption, with reported consumption usually smaller than reported production. This may imply some systematic source of under-reporting of consumption. Inaccuracies in natural gas volumetric data come from inherent limitations in the accuracy of natural gas metering, as well as from the usual problems of misreporting and timing differences. For example, natural gas consumption by electric utilities, as reported by the utilities, averaged about a 13-percent difference from natural gas consumption as reported by natural gas sellers in 1997.[4]

Petroleum. U.S. petroleum consumption is estimated on the basis of "petroleum products supplied," which means the volume of petroleum products shipped from primary storage facilities. Since there are only about 200 oil refineries in the United States, coverage of crude oil inputs and refinery outputs is generally complete. EIA requires a detailed breakdown and accounting of petroleum products produced by refineries, including refinery fuel. There are several reporting anomalies in EIA petroleum data:

- Each year more crude oil is supplied to refineries than can be accounted for by oil production, imports, and stock changes. This "unaccounted for crude oil" averaged 115,000 barrels per day, or less than 1.0 percent of refinery supply, in 1998.[5] Unaccounted for crude oil is likely due to imprecisions in recorded crude oil production, import, and stock change data. In EIA's *State Energy Data Report*, which presents consumption estimates, unaccounted for crude oil is included in consumption.

- Every year, several thousand more barrels per day of "unfinished oils" reach refineries than can be accounted for by sales and imports of unfinished oils.[6] In 1998, there were on the average 147,660 barrels per day of unaccounted for unfinished oils. The unfinished oil discrepancy is probably the result of asymmetric treatment of inter-refiner sales of unfinished oils. To the buyer, who knows the intended use of the product, it is motor gasoline or distillate fuel. To the seller, it is an unfinished oil. In the *State Energy Data Report*, the *Monthly Energy Review*, and this report, the unfinished oil discrepancy is accounted for through an adjustment to "other oils." The implication is that total oil consumption figures are more reliable than the exact distribution of consumption across specific petroleum products. Overall, it is likely that petroleum consumption estimates are accurate to within 5 percent.

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[2]Energy Information Administration, *Quarterly Coal Report*, DOE/EIA-0121(99/1Q) (Washington, DC, August 1999), Table 37, p. 42.
[3]Energy Information Administration, *Quarterly Coal Report*, DOE/EIA-0121(99/1Q) (Washington, DC, August 1999), Table 1, p. 1.
[4]Energy Information Administration, *Natural Gas Annual 1997*, DOE/EIA-0131(97) (Washington, DC, October 1998), Table A1, p. 228.
[5]Energy Information Administration, *Petroleum Supply Annual 1998*, DOE/EIA-0340(98)/1 (Washington, DC, June 1999), Table S2, pp. 6, 7.
[6]Energy Information Administration, *Petroleum Supply Annual 1998*, DOE/EIA-0340(98)/1 (Washington, DC, June 1999), Table 2, p. 34.

Nonfuel Use. Data for nonfuel use of petroleum products are more uncertain than those for total use of petroleum products. There are two main methods of estimating nonfuel use:

- Specialized petroleum products, such as petrochemical feedstocks, waxes and polishes, asphalt, and lubricants, are assumed to be dedicated to nonfuel use.

- Nonfuel use of conventional fuels is estimated on the basis of survey results from EIA's Manufacturing Energy Consumption Survey (MECS), with additional detail from trade association data and from known specific nonfuel uses (such as fertilizer feedstocks for natural gas).[7] MECS is a sample survey conducted only at 4-year intervals, with the sample optimized to detect the use of fuels for heat and power. Using MECS to measure nonfuel use requires interpolating between sample years and correcting for sampling problems associated with reported nonfuel use.

The main uncertainty in estimating carbon sequestered from nonfuel use is not the amount of product used but the fate of its carbon. The sequestration percentages used in this report are estimates, originally based on the typical fate of a particular class of products. The actual distribution of nonfuel uses of products is not always known with precision and could vary considerably from the "typical" usage; however, because sequestration through nonfuel use corresponds to only about 5 percent of total emissions, even large variations in the amount sequestered would have a small effect on estimated total emissions.

Conversion Factors

EIA oil and gas data are collected in volumetric units—barrels of oil and billion cubic feet of gas. Carbon emissions factors for fossil fuels usually take the form of tons of carbon per unit of energy content. Emissions factors are computed by dividing the carbon content (by weight) of a particular fuel by its energy content. Thus, in order to match an emissions factor to a fuel accurately, it is necessary to know its energy content with precision; and in the case of fuel quantity based on volumetric data, it is also necessary to know the density of the fuel. Each step that transforms the data from native units into more useful units inevitably reduces the precision of the resulting data, because the conversion factors are themselves statistical estimates or extrapolations, which may not precisely match the actual composition of the fuel.

Coal. Coal data are collected by State, coal rank, and weight (short tons). Electric utilities are asked to report both the rank and the energy content of the coal they burn. Since, in principle, utilities need to know the energy content of the fuels they purchase with precision, the energy content data should be fairly accurate. On the other hand, there is considerably more uncertainty in the rank or energy content of coal distributed outside the utility sector, which in 1998 accounted for about 13 percent of U.S. coal consumption.

The quality of coal can vary considerably within States and within a particular rank. Lignite, for example, is defined as containing 6,300 to 8,300 British thermal units (Btu) per pound, a range of about 15 percent. Subbituminous coal, by definition, has a range of 8,300 to 11,500 Btu per pound.[8] Thus, there may be errors of up to 15 percent in the industrial and residential/commercial coal conversion factors. On the other hand, residential/commercial and industrial coal consumption accounts for only about 5 percent of total U.S. energy-related carbon emissions, and even large errors would have only a small impact on the ultimate estimates.

Natural Gas. The composition of natural gas also varies considerably. In a 1992 survey of several thousand gas samples taken from local distribution companies around the United States, the Btu content ranged from 970 to 1,208 Btu per thousand cubic feet.[9] However, 80 percent of the samples fell within a much narrower range of 1,006 to 1,048 Btu per thousand cubic feet. Further, the average and median values of the samples fell within 0.3 percent of the national-level figure reported in EIA's *Natural Gas Annual*. This comparison suggests that EIA data on the energy content of natural gas are accurate to within 0.5 percent. This is not surprising, because local distribution companies monitor the energy

[7]Energy Information Administration, *Manufacturing Consumption of Energy 1994*, DOE/EIA-0512(94) (Washington, DC, December 1997), Table A3.

[8]Energy Information Administration, *Coal Industry Annual 1996*, DOE/EIA-0584(96) (Washington, DC, November 1997), pp. 252, 255.

[9]W.E. Liss et al., *Variability of Natural Gas Composition in Select Major Metropolitan Areas of the United States* (Chicago, IL: Gas Research Institute, March 1992), p. 14.

content of natural gas to ensure adherence to contractual specifications, and they report the average energy content to EIA.

Petroleum. The energy content of petroleum products varies more by volume than by weight. The density and the energy content of petroleum products are rarely measured by producers or consumers, and frequently they are not known with precision. Electric utilities measure the energy content of the residual oil they burn and report it to EIA. Liquid petroleum gases (propane, butane, and ethane) are pure compounds, and their energy content can be computed directly.

Liquid transportation fuels (jet kerosene, gasoline, and diesel fuel) are complex mixtures of many compounds, whose physical properties can vary considerably. Neither their density nor their energy content is measured by consumers or directly defined by product specifications. EIA estimates the energy content of these fuels on the basis of standard or "typical" values for each product. The standard energy contents for motor gasoline and kerosene-based jet fuel are drawn from a 1968 report produced by the Texas Eastern Transmission Corporation.[10] The energy content of distillate fuel oil is drawn from a Bureau of Mines Standard adopted in January 1950.[11] Jet fuel and diesel samples obtained for this report showed an average energy content that differs from EIA estimates by about 2 percent. Samples of motor gasoline analyzed by the National Institute of Petroleum and Energy Research displayed an average energy content that differs from EIA estimates by less than 0.5 percent. Reformulated gasoline, with the additives MTBE and TAME typically representing about 10 percent of its volume, can be expected to have an energy content about 1 percent lower than the energy content of standard gasoline. However, when collecting and disseminating motor gasoline data in units of energy, EIA does not use a distinct conversion factor for reformulated gasoline.

Carbon Emissions Coefficients

Carbon emissions coefficients are calculated by dividing the carbon content of a particular fuel (for example, 0.85 metric tons of carbon per metric ton of fuel) by the energy content of that fuel (for example, 43 million Btu per metric ton) to produce an emissions coefficient (in this example, 19.8 million metric tons of carbon per quadrillion Btu). Both the energy content and the carbon content of the fuel are subject to a degree of uncertainty. The carbon content of fuels has only an indirect and general bearing on their economic value and, consequently, is not necessarily collected by fuel producers or consumers. Although coefficients for coal and natural gas rely on analyses of a large set of fuel samples, coefficients for several petroleum products are based on "typical" or "representative" values, which may or may not perfectly reflect the underlying composition of the fuel. Variation in carbon content is limited to plus or minus 5 percent by the standard ratios of carbon to hydrogen in the hydrocarbon compounds that compose petroleum.[12]

Coal. There are large variations in the carbon and energy content of coals in different parts of the United States. Lignite may have as little as 12.6 million Btu per ton and contain 36 percent carbon, and anthracite may have as much as 98 percent carbon and an energy content as high as 27 million Btu per ton.[13] The carbon and heating values of coal are, in general, controlled by two factors:

- The ratio of flammable materials (carbon, hydrogen, and sulfur) to nonflammable impurities (moisture, ash, etc.)
- The ratio of carbon to hydrogen and sulfur within the flammable portion of the coal.

Most of the gross variation in both energy and carbon content (for example, between lignite and anthracite) is due to variations in nonflammable impurities. Consequently, if the Btu content of coal is estimated accurately, most of the variation in the carbon content is removed.

There is, however, residual uncertainty about the ratio of carbon to hydrogen and sulfur in particular coals. The carbon content of any particular coal sample can be determined by chemical analysis, but characterizing the average carbon

[10]Energy Information Administration, *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, December 1997), p. 497.
[11]Energy Information Administration, *State Energy Data Report 1995*, DOE/EIA-0214(95) (Washington, DC, December 1997), p. 496.
[12]Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1987-1992*, DOE/EIA-0573 (Washington, DC, November 1994), pp. 78-80.
[13]Energy Information Administration, *Coal Industry Annual 1996*, DOE/EIA-0584(96) (Washington, DC, November 1997), pp. 247-248, 252, 255.

content of national coal production creates some uncertainty. For this report, EIA relied on chemical analyses of several thousand coal samples, sorted by State of origin and coal rank, to compute national weighted average emissions coefficients (in million metric tons of carbon per quadrillion Btu) for each coal rank.

Natural Gas. Natural gas also varies in composition, but the range of variation is much smaller than that for coal. The emissions coefficient used in this report was based on an analysis of some 6,743 recent samples of U.S. natural gas. While there is some residual uncertainty about the exact carbon content of average U.S. natural gas, this uncertainty is on the order of 1 percent or less.

Petroleum Products. Crude oil is refined into a wide range of petroleum products, each presenting a different set of uncertainties. In general, the carbon content of petroleum products increases with increasing density. Uncertainties in emissions coefficients arise primarily from estimating the wrong density for a fuel or from mismatching the carbon and energy content of a particular fuel. The emissions factors for liquefied petroleum gas (LPG) and motor gasoline are probably accurate to within 1 to 2 percent. Coefficients for jet fuel and diesel fuel are probably accurate to within 2 to 4 percent, with much of the uncertainty centered in the standard heat contents used. The estimate for residual fuel is more uncertain but is probably accurate within 3 to 5 percent, as there are remaining uncertainties about the exact density and carbon content of the fuel.

The uncertainty for some minor petroleum products remains large, in some cases because it has proven difficult to identify exactly how reporters define particular product categories. Products with large remaining uncertainties include petrochemical feedstocks (density and portion of aromatics), lubricants, and waxes and polishes. The uncertainty of the emissions coefficients for these products is probably on the order of 10 percent. Because these products share a large nonfuel use component, their impact on the total carbon emissions figure is muted. Still gas is a highly variable byproduct of the refining process, which is then described as a petroleum product. Thus, the estimated emissions coefficient for still gas may vary by as much as 25 percent.

Adjustments to Energy

U.S. Territories. Energy data for U.S. territories present certain problems. Published petroleum data for Puerto Rico and the Virgin Islands are considerably less detailed than those for the mainland United States. In particular, there is no estimate of nonfuel use for these territories, and much of the petroleum consumption that could potentially be considered nonfuel use is lumped together into "other petroleum." Hence, the reliability of the emissions estimates is lower than that of petroleum emissions estimates generally.

Flare Gas. Estimates of emissions from flare gas are subject to uncertainty from two sources: estimates of the volume of gas flared, and the application of an appropriate emissions coefficient. Estimates of gas flared are based on State-reported volumes of gas "vented or flared" and a State-by-State estimate of the portion flared. The 1997 estimate of all vented and flared gas was 264 billion cubic feet.[14] States may define "vented" or "flared" gas differently. This suggests that estimates may be upwardly biased by the inclusion of nonhydrocarbon gases, such as hydrogen sulfide or carbon dioxide, in the statistics. Anecdotal reports from Wyoming, the State that represents approximately half of the estimated gas flared, indicate that most flaring is of nonhydrocarbon gases and that carbon dioxide emissions may be lower than estimated.

The emissions coefficient applied to flare gas represents the average coefficient for natural gas samples with heat contents between 1,100 and 1,127 Btu per standard cubic foot. EIA estimates the heat content of marketed gas at 1,107 Btu per standard cubic foot.[15] Anecdotal evidence suggests that most flared gas is flared at gas processing facilities, where the wet gas energy content would be representative. However, if flared gas is mostly "rich" associated gas with a heat content between 1,300 and 1,400 Btu per standard cubic feet, the current coefficient biases the estimates downward. Alternatively, it is possible that flare gas from treatment plants is "off spec" gas with a large content of hydrogen sulfide or inert gas and, hence, has an emissions coefficient lower than the one actually used.

[14]Energy Information Administration, *Natural Gas Annual 1997*, DOE/EIA-0131(97) (Washington, DC, October 1998), Table 3, p. 12.
[15]Energy Information Administration, *Annual Energy Review 1998*, DOE/EIA-0384(98) (Washington, DC, July 1999), Table A4, p. 320.

Other Sources of Carbon Emissions

The principal source of uncertainty in cement manufacture is the lime content of cement, which is estimated to within about 3 percent. There may also be limitations on the inherent accuracy of the Interior Department data used to calculate the estimate.

A second source of uncertainty, common to all the industrial estimates, is the use of stoichiometric computations to estimate emissions. This method calculates an emissions factor on the basis of a chemical reaction known to have taken place. It assumes, in effect, that the product (cement, lime, soda ash) is 100 percent pure, and that no raw materials are wasted in its production. In practice, impurities in the output would tend to reduce emissions below the stoichiometric estimate, whereas "wastage" of raw materials would tend to raise emissions above the estimate.

Excluded Sources

Appendix D lists several sources of emissions that are excluded because of uncertainty. Taking what is known about all excluded sources, additional emissions would probably be less than 10 million metric tons, or less than 1 percent of estimated emissions. Nonetheless, their exclusion does slightly bias the estimate downward. There are almost certainly other sources of carbon emissions unknown to the authors of this report. There is no way to estimate the impact of such unknown additional sources.

Methane

Estimates of methane emissions are, in general, substantially more uncertain than those for carbon dioxide. Only a portion of methane emissions are systematically measured. Where systematic measurements have been made, data are not comprehensive or collected for all sources in all years. In order to use these data to estimate emissions for the full population of emitters and to develop time-series emissions estimates, scaling mechanisms and sampling techniques must be applied, introducing additional error.

Where no systematic measurements have been made, estimation methods rely on a limited set of data applied to a large and diverse group of emitters. However, as additional data comes available each year, uncertainty in emissions estimates declines or, at a minimum, is more clearly delineated.

Coal Mining

Emissions from coal mines are currently the fourth-largest source of methane emissions in the United States—behind landfills, natural gas-related emissions, and domestic livestock—and they account for approximately 10 percent of national methane emissions. Methane emissions from coal mining have five sources: ventilation systems in underground mines, degasification systems in underground mines, surface mines, post-mining activities, and abandoned or closed mines. Only the first four are included in emissions estimates, because data on emissions from abandoned mines are lacking. The uncertainty associated with estimates of emissions from each of the sources included varies considerably and according to the year of the estimate. The exclusion of emissions from abandoned mines results in a downward bias in the estimates of methane emissions from coal mines. The bias probably is in the range of 0 to 20 percent of total coal mine methane emissions.[16] The overall uncertainty of the EIA estimates for emissions from coal mines is probably about 35 percent.[17]

Emissions from ventilation systems in the Nation's gassiest mines are measured on a quarterly basis by the Mine Safety and Health Administration (MSHA). A database, developed from these reports for all mines emitting more than 100,000 cubic feet of gas per day was compiled by the Bureau of Mines for the years 1980, 1985, 1990, and 1993. The Climate Protection Division of the U.S. Environmental Protection Agency (EPA) has since compiled a similar database for 1994,

[16]U.S. Environmental Protection Agency, Climate Protection Division, Coalbed Methane Outreach Program, *Draft Analysis of Abandoned Coal Mine Methane Emissions Estimation Methodology* (Washington, DC, December 18, 1998).

[17]S.D. Piccot, S.S. Masemore, E. Ringler, and D.A. Kirchgessner, "Developing Improved Methane Emission Estimates for Coal Mining Operations," Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium (U.S. Environmental Protection Agency, June 27-29, 1995).

through 1998. Although the measurements themselves should be reasonably accurate, each measurement represents a point in time. Variations in methane emissions across time (e.g., resulting from changes in operating practices) suggest an uncertainty in the range of 10 to 40 percent.

Estimates of emissions from the ventilation systems of nongassy mines are scaled to emissions estimates for 1988 developed by the EPA.[18] The EPA estimates emissions from nongassy mines at 2 percent of total emissions from the ventilation systems of underground coal mines. Thus, an error as high as 100 percent for this source would alter the total estimate by only 1 percent. This report uses mine-by-mine degasification data collected by the Environmental Protection Agency for the years 1993-1998.[19] For those years between 1988 and 1993, emission factors are interpolated and multiplied by production in mines with degasification systems. The level of uncertainty associated with the 1993-1998 estimates of degasification emissions is low.

Reliable measurements of emissions from surface mines are available for only five sites. Thus, estimates for this report were based on an emissions range supplied by the Intergovernmental Panel on Climate Change (IPCC).[20] The range of emissions suggested by the IPCC implies an uncertainty range of plus or minus 75 percent. However, estimates of emissions extrapolated from the five measured sites suggest an uncertainty level of less than 10 percent.[21] Assuming the larger uncertainty level would add only about 10 percent to the overall uncertainty of estimates of emissions from coal mines, because the volume of emissions from surface mines is relatively insignificant.

Emissions from post-mining activities are also estimated on the basis of an emissions range supplied by the IPCC, which implies an uncertainty in the area of plus or minus 60 percent. However, the magnitude of emissions from this source is similar to that of emissions from surface mines, thus also contributing about 10 percent to the overall uncertainty of coal mine emissions estimates.

Natural Gas Systems

Emissions estimates from natural gas systems are calculated on the basis of activity data and emissions for 86 separate gas industry process components. A recent study funded jointly by the EPA and the Gas Research Institute (GRI) provided point-in-time activity and emission factor estimates for each component during 1992.[22] To extrapolate estimates for other years from 1990 through 1998, activity data for each process component were associated with and scaled to a widely available data series, such as gross gas withdrawals or pipeline miles. The derived activity data were then applied to the 1992 emissions factor reported by EPA/GRI.

Despite capitalizing on an extended field sampling program and a statistical framework to meet predetermined accuracy goals, the EPA/GRI study still was forced to rely on a nonrandom sampling method that may not have been fully representative of the sample universe. Thus, there is uncertainty associated with both the activity factors and the emissions factors used in the original estimate. The uncertainty is further magnified by any additional error introduced by the scaling methods used for the activity data.

The uncertainty associated with activity data for 1992 varies dramatically across individual components, from as little as 2 percent to as much 1,114 percent. The uncertainty for emissions factors ranges from 5 percent to nearly 4,000 percent. These uncertainties are not necessarily correlated, and when they are combined to generate an emissions estimate from each component, the uncertainties are between 17 percent and 4,000 percent. On the other hand, because the largest

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[18]U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (Washington, DC, April 1993).

[19]U.S. Environmental Protection Agency, Office of Air and Radiation, *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines*, EPA-430-R-97-020 (Washington, DC, September 1997), and U.s. EPA, Ofice of Air and Radiation, Coalbed Methane Outreach Program.

[20]Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.108, web site www.ipcc.ch/pub/guide.htm.

[21]S.D. Piccot, S.S. Masemore, E. Ringler, and D.A. Kirchgessner, "Developing Improved Methane Emission Estimates for Coal Mining Operations," Presented at the 1995 Greenhouse Gas Emissions and Mitigation Research Symposium (U.S. Environmental Protection Agency, June 27-29, 1995).

[22]M.R. Harrison and R.M. Cowgill, *Methane Emissions From the Natural Gas Industry*, Prepared for the Gas Research Institute and the U.S. Environmental Protection Agency (June 1996).

emissions sources are associated with lower levels of uncertainty, the overall uncertainty of the national estimate is plus or minus 33 percent, probably increasing to on the order of plus or minus 40 percent after scaling activity data to more common industry metrics.

This report excludes methane emissions from the venting of gas. EIA collects data on gas vented or flared as reported by State agencies. The data reported by State agencies capture venting at many stages of the natural gas system. Thus, much of the reported venting is already captured under the existing EPA/GRI estimation method. Further, anecdotal information from Wyoming indicates that much of the gas reported to be vented is actually nonhydrocarbon gases that do not contribute to methane emissions. It is certain, however, that some methane is vented. The exclusion of such venting biases emissions estimate downward, perhaps by as much as 5 percent.

Combustion-Related Emissions

Most methane emissions from stationary combustion are the result of wood burning in residential woodstoves. Because estimates of wood consumption and of the condition and efficiency of residential woodstoves are highly uncertain, estimates of emissions from this source may vary by more than an order of magnitude.

Methane emissions from mobile combustion may be larger than the estimate in this report, but it is unlikely that they are significantly smaller. Emissions factors for mobile transportation assume a well-maintained fleet. A fleet of inadequately maintained vehicles may have as much as 10 times the level of emissions of a fleet of well-maintained or new vehicles. Although much of the U.S. fleet is well-maintained, a portion is old and/or poorly maintained.

Landfills

Estimates of methane emissions from landfills were broken into two sources: emissions from waste contained in 105 mostly large landfills with gas recovery systems and emissions from waste contained in all other landfills. Uncertainties associated with estimates of emissions for these two sources differ.

Emissions for many of the 105 mostly large landfills were estimated for 1992 on the basis of volumes of gas recovered and the efficiency of gas recovery.[23] Gas recovery efficiency was estimated with an associated uncertainty of plus or minus 25 percent. For years other than 1992, emissions from this source were estimated by using a model of landfill waste emissions that is benchmarked to the 1992 data. The model parameters include a low yield and high yield scenario that imply an uncertainty of 35 percent.

Emissions from all other landfills were also estimated from an emissions model, with parameters that could vary by 30 percent from the mean. A crucial input into the model is the amount of waste in place, which was calculated from estimates of waste landfilled annually between 1960 and 1998 and a regression equation to “backcast” waste flows from 1940 to 1960. The range of published estimates for years in which multiple sources were available suggests an uncertainty in the neighborhood of plus or minus 33 percent, and the error associated with the regression equation probably adds another 2 to 10 percent uncertainty.[24]

The ratio of waste in place in the 105 landfills to that in all other landfills was assumed to remain constant over time. This may be misleading, because the total number of landfills has been declining, with greater shares of waste believed to be directed toward larger landfills. Because those landfills with measured emissions for 1992 are likely to have higher-than-average emissions per ton of waste, the estimates for earlier years may be biased upward.

[23]S.A. Thorneloe, M.R.J. Doorn, L.A. Stefanski, M.A. Barlaz, R.L. Peer, and D.L. Epperson, “Estimate of Methane Emissions from U.S. Landfills,” Prepared for U.S. Environmental Protection Agency, Office of Research and Development (April 1994).

[24]Franklin Associates, Ltd., *Characterization of Municipal Solid Waste in the United States: 1994 Update* (prepared for U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response); and “The State of Garbage in America,” *Biocycle* (various years).

Domestic and Commercial Wastewater Treatment

Methane emissions from domestic and commercial wastewater treatment were estimated by IPCC's simplified approach,[25] which is based on the following assumptions: (1) each person contributes 0.5 kilogram per day of BOD_5 to municipal wastewater; (2) 15 percent of wastewater is treated anaerobically; and (3) anaerobic treatment yields 0.22 kilogram of methane per kilogram of BOD_5 treated. These assumptions were derived for developed countries in general, and there is considerable uncertainty about their specific applicability to the United States.

Per capita organic loadings of municipal wastewater in developed nations ranges from 0.024 to 0.091 kilogram BOD_5 per day. Organic loadings depend on such factors as the amount of kitchen wastes discharged into sewers and the degree to which industrial wastewater is discharged into municipal wastewater treatment systems. Wastewater treatment methods that are potential sources of methane include anaerobic digesters, facultative and anaerobic lagoons, and septic tanks. However, reliable information on the quantity of wastewater treated by each of these methods is not available. The IPCC emissions factor of 0.22 kilogram of methane per kilogram of BOD_5 is based on an estimate for lagoons in Thailand.[26] The applicability of this factor to treatment methods and climatic conditions in the United States is uncertain.

A further source of uncertainty is the ultimate fate of methane generated from wastewater in the United States. As in the case of landfill methane, wastewater methane generated in sewage treatment plants is often combusted to control odors or emissions of volatile organic compounds. Conceptually, the amount of methane combusted should be deducted from estimated emissions, but EIA is not aware of any information on the amount or extent of combustion of off-gases from sewage treatment plants.

Enteric Fermentation in Domesticated Animals

Estimates of methane emissions from enteric fermentation are a function of an emissions factor for each animal group, based on their diet and energy usage multiplied by their population. The magnitude of typical revisions to animal population data by the U.S. Department of Agriculture suggests that population estimates are likely to be accurate within 5 percent. The energy requirements and diets of cattle—by far the largest source of emissions from enteric fermentation— have been carefully studied. For dairy cattle, energy requirements are largely a function of milk production. This report uses State-level data and regional emissions factors for dairy cattle, scaled to milk productivity provided by the EPA.[27] The reduction in uncertainty caused by regional variation should lower overall uncertainty associated with this source by 1 to 2 percent.

There is also some uncertainty associated with the average size of cattle, which could affect the animals' energy requirements. Cattle sizes have changed rapidly over the past decade in response to market forces. This report uses slaughter weights as a proxy for average animal size and scales emissions factors for beef cattle to animal size, a method that may be imperfect. The slaughter sizes vary over time by approximately 33 percent. There is some uncertainty associated with estimates of the energy requirements of animals other than cattle, but even if this uncertainty were as high as 50 percent, the impact on the overall estimate would be no more than 3 percent.

Solid Waste of Domesticated Animals

Uncertainty in estimates of animal populations is on the order of 5 percent or less. Emissions are largely a function the amount of waste an animal produces. The amount of waste produced is a function of size, productivity, and diet. Thus, changes in animal sizes, which are difficult to monitor, create uncertainty. As discussed above, slaughter weights have

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[25]Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Vol. 3 (Paris, France, 1997), pp. 6.15-6.23, web site www.ipcc.ch/pub/guide.htm.

[26]U.S. Environmental Protection Agency, *International Anthropogenic Methane Emissions: Estimates for 1990*, EPA 230-R-93-010 (Washington, DC, January 1994), p. 10-15.

[27]U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998,* (Washington, DC, April 2000), web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

been used as an imperfect measure of changes in the size of beef cattle. This proxy measure varies by about 33 percent over time.

The maximum amount of methane that a given amount of an animal's waste can produce under optimal anaerobic conditions can be measured fairly accurately in the laboratory. The share of that production realized under various waste management regimens is much more uncertain. Waste management systems and the portion of potential methane emissions realized vary across States. The use of State-level population data and methane conversion factors for the waste of dairy cattle provided by the EPA[28] should marginally lower overall uncertainty associated with estimates from this source.

Emissions also vary with ambient air temperatures and, depending on the waste management system, may change by anywhere from 1 to 60 percent. For this report, all animal waste was assumed to be managed at air temperatures between 59 and 77°F. Overestimating the average temperature at which waste is managed would bias emissions estimates upward.

Wetland Rice Cultivation

There are large uncertainties associated with the estimate of methane emissions from wetland rice cultivation. Emissions estimates are based on several studies of rice paddies in the United States, which provide daily emissions rate ranges. Studies have shown large seasonal and time-of-day variations in methane flux. Many variables affect methane production in rice fields, including soil temperature, redox potential, and acidity; substrate and nutrient availability; addition of chemical and/or organic fertilizers; rate of methane oxidation; and rice plant variety. The wide range of emissions provided by different researchers suggests an uncertainty of several hundred percent.[29]

Crop Residue Burning

Estimates of emissions from the burning of crop residues are calculated on the basis of a carbon content of about 45 percent of dry matter, as recommended by the IPCC,[30] and a 3-percent burn rate for all crop residue except rice in California, as recommended by the EPA.[31] The carbon content probably is accurate to plus or minus 10 percent. The 3-percent burn rate used for all States but California is likely to have a small uncertainty. The more variable burn rate for California may have greater uncertainty but affects a very small portion of emissions.

Chemical Production

Estimates of methane emissions from chemical production are highly uncertain because of the wide variety of production processes and inputs. Organic chemical production requires the cracking and reforming of hydrocarbon bonds. How the bonds crack and reform depends on several variables, including the composition of the feedstock, the temperature of the reaction, the catalyst used, and the reaction vessel. As a result, the quantities of products and byproducts, including methane, vary. Methane may be released through leaks in seals and valves. Therefore, methane emissions are dependent on the operation and maintenance practices of the producer.

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[28]U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, (Washington, DC, April, 2000), web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

[29]R.J. Cicerone, J.D. Shetter, and C.C. Delwiche, "Seasonal Variation of Methane Flux from a California Rice Paddy," *Journal of Geophysical Research*, Vol. 88 (1983), pp. 7203-7209; C.W. Landau and P.K. Bolich, "Methane Emissions from Louisiana First and Ratoon Crop," *Soil Science*, Vol. 156 (1993), pp. 42-48; R.L. Sass, F.M. Fisher, S. Lewis, M. Jund, and F. Turner, "Methane Emissions from Rice Fields: Effect of Soil Properties," *Global Biogeochemical Cycles*, Vol. 8 (1994), p. 135; R.L. Sass, F.M. Fisher, and Y.B. Wang, "Methane Emissions from Rice Fields: The Effect of Floodwater Management," *Global Biogeochemical Cycles*, Vol. 6 (1992), pp. 249-262.

[30]Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), pp. 4.67-4.86, web site www.iea.org/ipcc/invs6.htm.

[31]U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-1998*, (Washington, DC, April, 2000), web site www.epa.gov/globalwarming/publications/emissions/us2000/index.html.

Iron and Steel Production

There is substantial uncertainty associated with estimates of methane emissions from iron and steel production, with the plausible range of estimates ranging from 80 percent below the point estimate presented in this report to 100 percent above the point estimate. Several factors may constrain methane emissions from iron and steel production. The pollution controls used on coke ovens to prevent emissions of volatile organic compounds usually eliminate methane as well. Exhaust gases from blast furnaces that are typically captured and used for fuel contain methane. Because the emissions factors used in this report are global emissions factors provided by the IPCC,[32] they may not accurately portray the level of emission controls found in U.S. plants. Further, the efficacy of pollution control systems is likely to vary with operation and maintenance techniques.

Excluded Sources

Appendix D lists several sources excluded because of excessive uncertainty or insufficient data. Known sources excluded from methane emissions estimates are industrial wastewater, abandoned coal mines, industrial landfills, and open dumps. There are other sources of methane that have yet to be identified and thus are absent from emissions estimates. Excluded sources would invariably add to total emissions, but the magnitude of the additions is impossible to estimate.

Nitrous Oxide

Many sources of nitrous oxide emissions are difficult to quantify, and estimates are highly uncertain. Nitrous oxide has been viewed as a minor contributor to overall U.S. greenhouse gas emissions, and until recently few resources have been devoted to improving measurement and estimation methods. However, the inclusion of nitrous oxide in the Kyoto Protocol has increased the attention given to nitrous oxide. Uncertainties are likely to be reduced as additional research focuses on nitrous oxide emissions.

Mobile Sources

Nitrous oxide emissions from mobile sources are, after nitrogen fertilization of soils (see below), one of the largest sources of uncertainty in the total estimate. Nitrous oxide is emitted from motor vehicles equipped with catalytic converters, but the conditions under which the emissions are produced are not well defined. Research evidence indicates that catalytic converters can convert nitrogen oxides (NO_2) into nitrous oxide (N_2O) when they are operating at relatively low temperatures, but that full conversion to ordinary nitrogen (N_2) occurs when the catalytic converter is operating at its normal operating temperature.

Estimating national-level nitrous oxide emissions from this source thus presents a daunting challenge, because emissions depend on:

- Whether or not vehicles are equipped with catalytic converters, and the type of catalytic converter
- The portion of the vehicle fleet with properly functioning catalytic converters
- National average “driving cycles,” indicating the portion of the time the national vehicle fleet that is driven with warm (but neither hot nor cold) catalytic converters.

In 1997, the IPCC published new emissions factors that were some four times higher than the emissions factors used in earlier editions of *Emissions of Greenhouse Gases in the United States*. The origin of the new emissions factors lies in a confluence of two events: scientific research indicated significant missing sources of nitrous oxide; and an emissions

[32]Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 2.22, web site www.iea.org/ipcc/invs6.htm.

report published by the Canadian government, based on recent research,[33] indicated much higher Canadian emissions of nitrous oxide from mobile sources than had been anticipated. The research subsequently found its way into the revised IPCC guidelines and into work undertaken by the former EPA Office of Policy, Planning, and Evaluation.[34] The EPA Office of Mobile Sources reacted by mounting a program of testing U.S. motor vehicles for nitrous oxide emissions in June and July 1998. Preliminary results, published in August 1998, recommend emissions factors for U.S. use that are about 25 percent higher than those used by EIA in 1997 and about one-third the magnitude of those recommended by the IPCC.[35]

The work done by EPA's Office of Mobile Sources indicated that the linkage between the Canadian research and the emissions factors actually used in the Canadian inventory was weak, and that the emissions factors used in the Canadian inventory were at least 50 percent higher than would be indicated by the underlying research. Further, the Canadian tests were undertaken using test gasoline with sulfur levels at least twice the U.S. average, and the U.S. testing indicated that, by affecting the catalytic converter, the higher sulfur content may have greatly increased nitrous oxide emissions. However, all the tests of motor vehicles for nitrous oxide emissions reported in the literature involve fewer than 50 vehicles combined, and the sampling of the vehicles is neither random nor representative. Vehicles have also been tested under a limited range of conditions. Test results to date have been, as noted, highly variable, and we do not yet have a complete understanding of the causes of motor vehicle nitrous oxide emissions.

The largest single influence on nitrous oxide emissions is how the vehicle is driven or, at the national level, the characteristics of the national average trip. In the Canadian tests, automobiles driven in the "highway mileage test" (used to calculate the figures shown on the "highway mpg" sticker on new cars) had emissions per kilometer about one-fourth the level of *the same vehicles* driven over the "Federal test program" (used to show compliance with Federal emissions standards). The highway mpg test uses a warm start, an average distance of 20 miles, and an average speed of 40 mph. The Federal test program simulates a 9.5-mile, stop-and-go, 19 mph average from a cold start. It would be reasonable to conclude that a high level of emissions occurs at the cold start, which is then allocated over some number of miles. The longer the trip, the lower the emissions per mile.

The IPCC emissions factors are calculated in grams of nitrous oxide per kilometer driven, but the actual relevant emissions would seem to be grams of nitrous oxide per cold start. If the length and character of the "national average trip" approximates the trip used to calculate the emissions factor, then the emissions factor gives the correct result. The EPA designed the Federal test program to resemble the "national average trip," as determined by the U.S. Department of Transportation's National Personal Transportation Survey. This implies that the EPA's emissions factors may be reasonable as a first approximation. There are, however, several potential sources of uncertainty:

- **Potential for the Wrong Model of Emissions.** It may turn out that a "per unit fuel consumption" or a "per trip" model of emissions produces more accurate results than the current "per kilometer" method. This is particularly the case in that national gasoline consumption is easier to measure than national vehicle miles traveled.

- **Uncertainties About the Correct Emissions Factors.** At present, there is a tremendous (fourfold) variation in observed emissions factors (measured in grams per kilometers) across different catalytic-converter-equipped vehicles and across the same vehicle subject to multiple tests or different tests. Under the circumstances, there can be little assurance at present that the emissions factors that are being used are closely representative of on-road emissions factors.

- **Uncertainties About Activity Data.** At present, the EIA emissions estimates are based on estimates of national vehicle miles traveled, drawn from the Federal Highway Administration (FHWA) and partitioned by vehicle type and vintage. Total national vehicle miles traveled are drawn from a variety of State surveys of varying quality, undertaken for varying purposes. In recent years, the States have experienced great difficulty in accurately partitioning data between cars and light trucks, given recent increases in sales of light trucks as automobile substitutes. The

[33]A. Jaques, F. Neitzert, and P. Boileau, *Trends in Canada's Greenhouse Gas Emissions (1990-1995)* (Ottawa: Environment Canada, October 1997, pp. 23-24. The cited research was: V. Ballantyne, P. Howes, and L. Stephanson, *Nitrous Oxide Emissions From Light Duty Vehicles*, SAE Technical Paper 940304 (March 1994).

[34]Now the EPA Office of Policy Economics and Innovation.

[35]U.S. Environmental Protection Agency, *Emissions of Nitrous Oxide From Highway Mobile Sources*, EPA-420-R-98-009 (Washington, DC, August 1998), web site www.epa.gov/oms/climate.htm. The author of this report is Harvey Michaels.

partitioning is important for nitrous oxide emissions, because light-duty vehicle emissions factors are about 50 percent higher than automobile emissions factors. The FHWA recently revised the "split" between cars and light trucks for data back to 1993 but has not revised 1992 and earlier data.

- **Variations by Model Year.** The new emissions factors vary considerably by model year, with very low factors for pre-1983 model cars, higher factors for 1983-1995 model cars, and lower factors for post-1996 model cars. Thus, the partitioning of vehicle miles traveled between cars and light trucks, and by model year, is a source of added uncertainty.

In summary, the largest uncertainty is associated with the emission factors themselves. The range of reported emissions factors might vary by as much as a factor of 4. Choosing the incorrect model of emissions could also produce large (but probably less than 100 percent) errors. The problems associated with the activity data are of smaller magnitude, but still substantial. An imprecise partitioning of vehicle miles traveled between cars and trucks could push emissions up or down by perhaps 10 to 20 percent. The estimate of total vehicle miles traveled is more reliable than its components, particularly in view of the number of independent checks (such as gasoline consumption) that prevent the aggregate data from wandering too far from the (unobservable) actual values.

Stationary Source Combustion

As the result of improved studies, emissions factors recommended by the IPCC are now limited to one value for each fuel type, regardless of application. Although the emissions factor for coal is 1.4 kilograms of nitrous oxide per terajoule of energy input, emissions may range from 0 to 10 kilograms. For oil, the recommended emissions factor is 0.6 kilogram, with a possible range of 0 to 2.8 kilograms. The range is smallest for natural gas (0 to 1.1 kilograms), with 0.1 kilogram as the suggested factor.[36] The emissions factors were derived from studies of "conventional" combustion facilities (those equipped with burners and grate combustion, with flame temperatures well above 1,000°C).

The underlying "problem" with estimating nitrous oxide emissions from combustion is that high-temperature combustion, by itself, apparently does not create much nitrous oxide, and it may destroy nitrous oxide. Under some circumstances, however, nitrogen oxides (NO, NO_2, and NO_3), which are combustion byproducts, may react to form nitrous oxide in exhaust stacks, sample bottles used for testing emissions, or perhaps in the atmosphere after being emitted. The existence of this circumstance has made it difficult to measure emissions accurately and raises the possibility that stationary combustion, through the medium of NO_x emissions, may ultimately prove to be a larger source of nitrous oxide than currently estimated.

Solid Waste of Domesticated Animals

Similar to methane emissions from the solid waste of domesticated animals, nitrous oxide emissions are a function of animal populations, volatile solids production, the nitrogen content of the volatile solids, and how efficiently the manure management system used converts nitrogen to nitrous oxide. Uncertainty in estimates of animal populations is on the order of 5 percent or less. Volatile solids content, the nitrogen content of the waste of each species, manure management systems, and nitrogen to nitrous oxide conversion rates are from the IPCC.[37] The IPCC emissions factors were derived from limited data and are global averages, which may differ from U.S. averages. Also, the IPCC factors show an identical nitrogen to nitrous oxide conversion rate for both anaerobic lagoons and liquid/slurry management systems. These systems are likely to have different nitrous oxide yields.

[36]Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Vol. 3 (Paris, France, 1997), p. 1.36, web site www.ipcc.ch/pub/guide.htm.

[37]Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual*, IPCC Guidelines for National Greenhouse Gas Inventory, Vol. 3 (Paris, France, 1994), pp. 4.94-4.110.

Nitrogen Fertilization of Agricultural Soils

The activity data supporting these estimates vary in reliability. Estimates of the nitrogen content of chemical fertilizer consumption, based on U.S. Department of Agriculture and trade association statistics, are probably reasonably reliable. However, nitrogen fertilizer accounts for only about one-quarter of the nitrogen applied to agricultural soils. The balance is accounted for by animal manure, and the plowing under of crop residues. The accounting of the volume and disposition of animal manure can be accurate only in a general way, because it is itself a calculated figure (number of animals times manure per animal times share spread on soils times nitrogen content of manure), in which all the variables (except animal populations) have only a moderate (plus or minus 25 percent) degree of certainty. The accounting worsens for agricultural residues, because this calculated figure (crop times residue ratio times nitrogen content times share not combusted) systematically undercounts failed crops, and the residue ratio and nitrogen contents can have only a moderate degree of certainty. Nonetheless, the actual nitrogen application to agricultural soils from all three sources, taken together, is probably within 50 percent of the actual (unobservable) figure.

The consequences of applying nitrogen to agricultural soils are far more problematic. Nitrous oxide emissions occur when a particular class of nitrous-oxide-emitting bacteria expand their ecological niche in agricultural soils. The bacteria compete with other, with non-emitting bacteria, and with plants to consume soil nitrogen. Thus, actual emissions from any particular plot of land will be determined by whether conditions are propitious, and they may range from nil to at least twice the national average emissions factor.

Conditions can be “propitious” for bacterial action generally, or specifically for nitrous-oxide-emitting microbes. Propitious conditions include high soil temperatures, adequate moisture, and soil that is neither too acid nor too alkaline, not too compacted, etc. Nitrogen fertilizers can also be deployed in ways that are more or less prone to stimulate bacterial action. Both scientific understanding of the conditions that promote nitrous-oxide-emitting bacteria and suitably detailed knowledge about the conditions on American farmlands for the calculation of more detailed and accurate emissions factors are absent at present. Thus, whatever the state of the activity data, the emissions factors applied can only be considered accurate to plus or minus 100 percent.

Crop Residue Burning

The accuracy of emissions estimates for crop residue burning is limited, because the practice of burning crop residues in the United States has not been systematically quantified. As described above in the discussion of methane emissions from crop residue burning, a default figure of 3 percent was used in the calculation, with the exception of California.

Waste Combustion

Nitrous oxide emissions from waste combustion are estimated by multiplying the volume of waste combusted annually by an emissions factor for each ton combusted. Data on waste combustion probably are accurate to within plus or minus 33 percent, but the emission factor may vary by an order of magnitude.

Human Sewage in Wastewater

Emissions from human sewage in wastewater are a function of U.S. population, per capita protein intake, and the conversion rate of nitrogen to nitrous oxide during wastewater treatment. Population and per capita protein intake have a very small error band, but the rate at which nitrogen is converted to nitrous oxide is highly uncertain. The conversion rate is altered by the presence or absence of oxygen, wastewater temperatures, and acidity. In the absence of other data, a global average emissions factor provided by the IPCC was applied.

Adipic Acid Production

For adipic acid production, emissions estimates are based on three data inputs: production activity, an emissions factor, and emissions abatement activity. The primary sources of uncertainty are the amount of production at plants with emissions abatement and the effectiveness of the abatement techniques in eliminating nitrous oxide. In addition, the emissions factor for adipic acid production was determined by stoichiometry. Because plant-specific production figures

must be estimated by disaggregating total adipic acid production on the basis of existing plant capacities, any national estimate will be an imprecise figure if the conversion of nitric acid to adipic acid is less than 100 percent efficient.

Nitric Acid Production

The emissions factor for nitric acid production is also uncertain. It is drawn from measurements at a single DuPont plant, which indicate a range of emissions from 2 to 9 grams of nitrous oxide per kilogram of acid production. Because the midpoint of the range was used in the calculation, estimates may err by as much as 65 percent. Applying the emissions factor range to total production also adds uncertainty, because the emissions reported at the DuPont plant may not be representative of emissions at all nitric acid production plants.

HFCs, PFCs, and Sulfur Hexafluoride

Emissions of hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride are drawn from the work of the EPA. In general, most of these compounds are manufactured chemicals, and the amounts produced and sold can be determined, despite the fact that actual production and sales are not reported to the U.S. Government. On the other hand, the flow from sales of manufactured chemicals to emissions from their use is based on model output, particularly for HFC-134a and other refrigerants.

There are also significant fugitive emissions of these compounds, including the formation of perfluoroethane and perfluoromethane from aluminum smelting, fugitive emissions of sulfur hexafluoride from magnesium smelting, and emissions of HFC-23 from the manufacture of HCFC-22. The uncertainty of the estimates is probably on the order of 30 to 50 percent.